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INFLUENCE OF SAMPLE DISTURBANCE ON SAND RESPONSE TO CYCLIC LOAD--ETC(U)  
JAN 77 K MORI, H B SEED, C K CHAN

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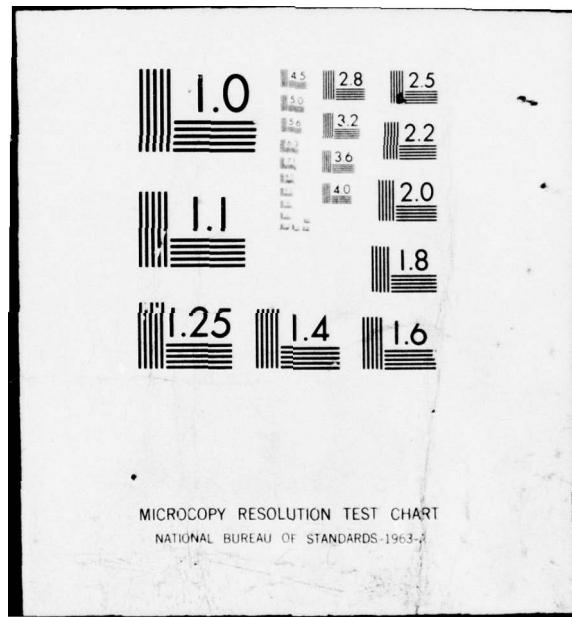
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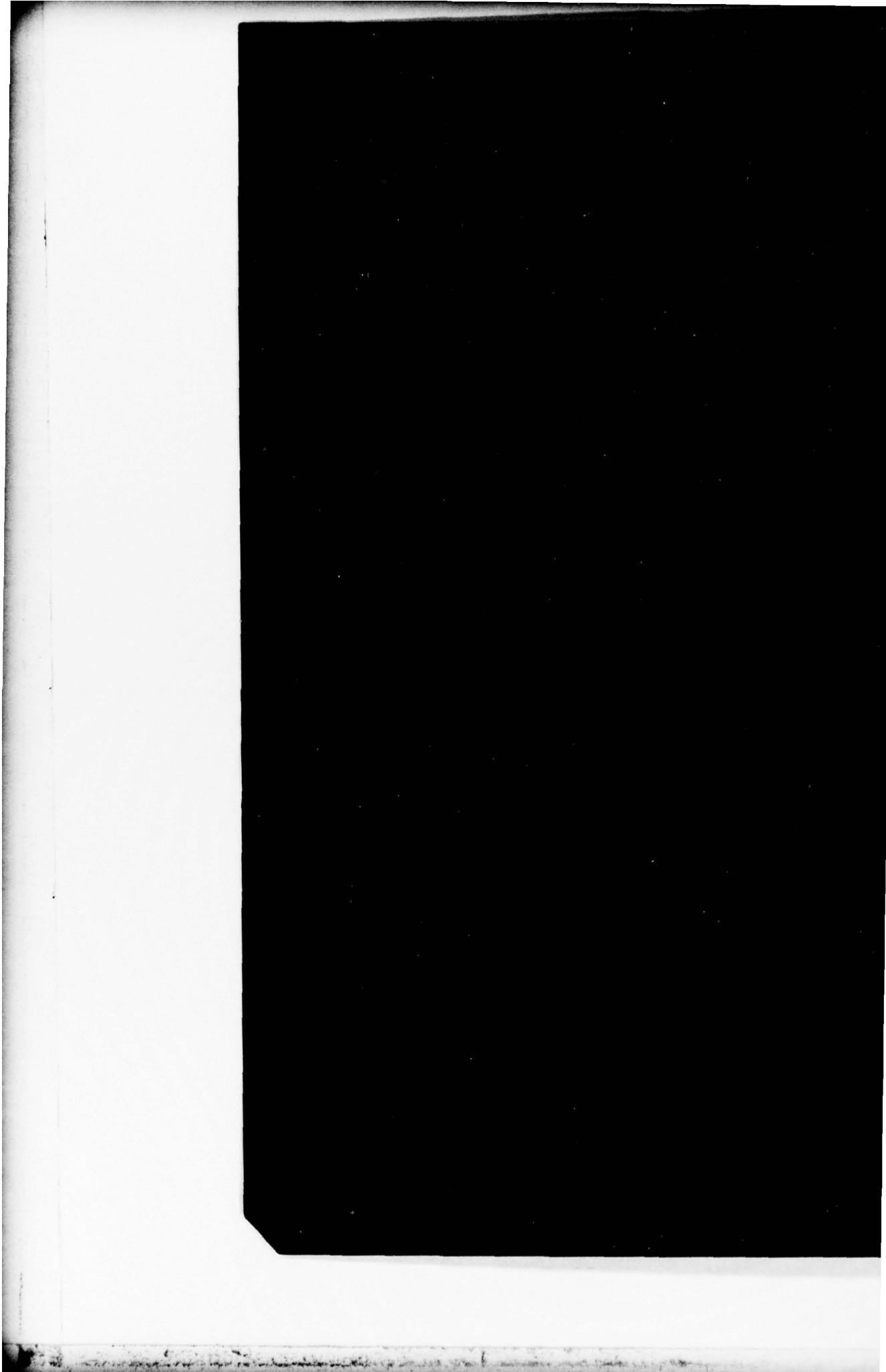
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20. ABSTRACT (Continued)

→ performance are to be made on the basis of laboratory tests. This report presents the results of a study of sample disturbance during extraction and handling on the liquefaction characteristics of a sand having an artificially induced increased resistance to liquefaction due to the application of a prescribed prior strain history. It is shown that the effects of this strain history are for practical purposes obliterated by the sampling and handling procedure and suggestions are made for assessing the significance of such effects in the practical evaluation of laboratory test results. ←

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PREFACE

This report was prepared by Drs. Kenji Mori, H. Bolton Seed, and Clarence K. Chan under Contract DACW 39-75-M-4888 as part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES) under CWIS Work Unit 31144, "Earthquake Stability of Earth and Rock Fill Dams."

The work was monitored by Dr. A. G. Franklin of the Earthquake Engineering and Vibrations Division (EE&VD), Soils and Pavements Laboratory (S&PL), WES. General guidance was provided by Messrs. J. P. Sale and S. J. Johnson, Chief and Special Assistant, respectively, S&PL, and Dr. F. G. McLean, Chief, EE&VD. OCE technical monitor for this study was Mr. Ralph Beene.

Directors of WES during the preparation and publication of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. The Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)  
AND METRIC (SI) TO U. S. CUSTOMARY UNITS

Units of measurement used in this report can be converted as follows:

Multiply \_\_\_\_\_ By \_\_\_\_\_ To Obtain \_\_\_\_\_

U. S. Customary to Metric (SI)

inches	2.54	centimetres
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
degrees (angle)	0.01745329	radians

Metric (SI) to U. S. Customary

millimetres	0.0393701	inches
centimetres	0.393701	inches
kilograms	2.20462	pounds
kilograms per square centimetre	14.2233	pounds per square inch

Influence of Sample Disturbance on Sand Response To Cyclic Loading

by

Kenji Mori<sup>1</sup>, H. Bolton Seed<sup>2</sup> and Clarence K. Chan<sup>3</sup>

Introduction

One of the major developments in the evaluation of the cyclic liquefaction characteristics of sand deposits has been the recognition that these properties are influenced not only by the density of the deposit but also by such factors as the structure of the sand grains, the seismic history of the deposit, the coefficient of lateral earth pressure for the in-situ conditions, and the age of the deposit. Accordingly importance has correctly been given to the necessity for obtaining and testing truly undisturbed and representative samples if meaningful evaluations of liquefaction potential are to be made.

The extent to which this can be achieved is clearly influenced by the degree to which undisturbed samples of sand can be obtained without significantly affecting their in-situ characteristics. It has long been recognized that recovering undisturbed samples of sand from the ground constitutes one of the most difficult of soil investigation techniques, but primary emphasis has been placed on the possible changes in density which may occur in the sampling process. In a series of carefully conducted investigations some twenty years ago, engineers of

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<sup>1</sup> Graduate Research Assistant, Department of Civil Engineering, University of California, Berkeley.

<sup>2</sup> Professor of Civil Engineering, University of California, Berkeley, California.

<sup>3</sup> Research Engineer, University of California, Berkeley, California.

the Corps of Engineers Waterways Experiment Station (1952) showed clearly that even with the best sampling procedures, there was a tendency for very loose sands to be densified and for dense sands to be loosened during the sampling process. Accordingly efforts have been directed toward minimizing these effects as far as possible.

However with the recognition that the properties of sands are also significantly influenced by the structural arrangements of the grains, by prior shear strains produced by the seismic history and by sustained vertical and lateral earth pressures due to their geologic history, emphasis must now also be placed on maintaining the structural arrangement of grains as well as their in-place density. While general agreement seems to exist on most of these matters, there are still some points for debate. Thus while many engineers have contended that the cyclic liquefaction resistance of sands is reduced by the sampling process, others have argued that the small vibratory strains induced during sampling may cause the samples to have greater resistance to cyclic stress applications than the in-situ material.

The study described in the following pages was conducted to clarify some of the significant factors affecting the cyclic liquefaction characteristics of sands and to determine the extent to which they are influenced by the sampling process. Particular emphasis was placed on the influence of sample disturbance and other sources of small strains on the cyclic liquefaction characteristics of sand, but other factors pertinent to the overall problem are reviewed in the following pages for the purpose of making a general evaluation of sample disturbance effects on this important aspect of soil behavior. The discussion is

limited to the behavior of horizontal sand deposits in which initial liquefaction may be induced by the development of horizontal cyclic shear stresses of approximately equal magnitude in cyclically reversing directions, say by an earthquake or by wave forces on a submerged structure, although many of the same principles are applicable to sloping deposits in which some type of liquefaction may develop.

For purposes of clarification, the following terminology will be used throughout the discussion:

"Liquefaction": denotes a condition where a soil will undergo continued deformation at a constant low residual stress or with no residual resistance, due to the build-up and maintenance of high pore water pressures which reduce the effective confining pressure to a very low value; pore pressure build-up may be due either to static or cyclic stress applications.

"Initial Liquefaction": denotes a condition where, during the course of cyclic stress applications, the residual pore water pressure on completion of any full stress cycle becomes equal to the applied initial effective confining pressure; the development of initial liquefaction has no implications concerning the magnitude of the deformations which the soil might subsequently undergo; however, it defines a condition which is a useful basis for assessing various possible forms of subsequent soil behavior.

"Initial Liquefaction with Limited Strain Potential" or "Cyclic Mobility": denotes a condition in which cyclic stress applications cause limited strains to develop either because of the remaining resistance of the soil to deformation or because the soil dilates, the

pore pressure drops, and the soil stabilizes under the applied loads.

#### Characteristics of Natural Sand Deposits

While cyclic liquefaction problems sometimes arise in connection with compacted sand fills, the majority of problems are related to natural deposits of cohesionless soils. Such deposits are frequently the result of fluvial deposition or sedimentation in a fluvial, marine or lacustrine environment. The resulting structure is probably most closely akin to that produced in the laboratory by sedimentation or pluvial deposition, both of which appear to lead to similar liquefaction characteristics. However the lateral translation associated with fluvial deposition or even hydraulic fill techniques may lead to a somewhat different grain structure than that caused by direct sedimentation in the laboratory. For this reason, the structure immediately after placement may be more analogous to that resulting from pluviation in the laboratory where some degree of lateral movement of particles is also involved.

After initial deposition, the overburden pressure in a normally consolidated deposit of sand will increase gradually and the sand will eventually attain a condition of equilibrium under the overburden pressure to which it is subjected. The properties of the deposit will nevertheless be influenced to a large degree by the geologic history to which it is subjected. This may involve:

- (1) An increase in density of sands deposited in a loose condition as the effective overburden pressure increases.
- (2) An increase in the coefficient of earth pressure at rest if the soil is overconsolidated due to deposition and subsequent

erosion or due to seismically-induced cyclic strains.

- (3) The inducement of a more stable structure due to the seismic history of the environment in which it is located.
- (4) Increased stability due to some degree of cementation or welding at points of contact due to the prolonged period of stress to which it is subjected or to the development of a more stable structure due to secondary compression effects.

Thus the final properties of the deposit are likely to depend on at least five factors.

1. The density or relative density of the soil.
2. The structure at placement or deposition.
3. Cementation or contact point welding due to the application of sustained pressure over a prolonged period of time or secondary compression effects on the soil structure.
4. The seismic history, which may cause a small but significant change in structure or a change in  $K_o$ .
- and 5. The possible effects of overconsolidation, determined by the overconsolidation ratio and the resulting value of  $K_o$ .

Each of these factors will in turn affect the liquefaction characteristics under cyclic or seismic loading conditions. The potential magnitude of these effects is reviewed briefly below.

#### In-situ Factors Affecting Soil Liquefaction Characteristics

Based on recent investigations it seems reasonable to conclude that the liquefaction characteristics of a sand, in-situ are influenced by the various factors discussed above as follows:

### 1. Relative Density

Since the earliest studies of sand liquefaction under cyclic loading conditions, it has been recognized that the cyclic stresses required to cause liquefaction can conveniently be expressed in terms of the cyclic stress ratio; that is the ratio of the applied cyclic shear stress to the initial effective vertical stress on the plane on which the cyclically reversing shear stresses are applied. Much data of this type has been presented in the literature but perhaps the most comprehensive study is that reported by DeAlba et al (1975) using large scale simple shear test specimens (90" x 42" x 4") of Monterey No. 0 sand at different relative densities. This sand has a mean grain diameter of 0.36 mm and a coefficient of uniformity of 1.5. The values of cyclic stress ratio causing initial liquefaction of this sand at different relative densities are shown in Fig. 1. The important effect of density of sand on the stresses causing initial liquefaction is readily apparent.

It is also important to note that the test data obtained from this large scale investigation showed clearly that for sand at any given relative density, there was apparently a limited amount of shear strain that could be developed, regardless of the number of stress cycles applied and varying only slightly with the magnitude of the applied stress ratio, unless the full undrained strength of the soil were exceeded. Typical results for tests on Monterey No. 0 sand at different relative densities are shown in Fig. 2. Although some extrapolation and interpretation of the data is required, it may be seen from the data in this figure that at relative densities less than about 40 percent,

the application of cyclic stress ratios sufficiently high to cause initial liquefaction will apparently cause extremely high and probably unlimited strains in the soil. This corresponds to a condition of true liquefaction. However, for relative densities greater than about 45 percent, the application of stress ratios and numbers of cycles sufficiently high to cause initial liquefaction would result in only a limited amount of shear strain, the limiting strain potential decreasing with increasing relative density. Thus for example, the limiting strain potential for a sample with a relative density of 50 percent might be about  $\pm 35$  percent but a sample with a relative density of 90 percent would have a limiting strain potential of only about  $\pm 6$  percent. This type of behavior is clearly described by the term "initial liquefaction with limited cyclic strain potential". Strains exceeding the cyclic strain potential would require the application of stresses approaching the strength of the sand under monotonic loading conditions.

The condition of "initial liquefaction with limited strain potential" as used above is directly analogous to the condition of "cyclic mobility" used by Casagrande (1976) and Castro (1975). However, the authors prefer the use of the former term for several reasons (Seed, Arango and Chan, 1975).

- a. "Cyclic mobility" does not serve to indicate that high residual pore water pressures exist in the soil, whereas "initial liquefaction" clearly indicates such a condition.
- b. "Cyclic mobility" covers a wide range of conditions with potential strains ranging from almost zero to several tens of percent. Thus under some situations, a condition of cyclic mobility may be perfectly acceptable, whereas in others, it would

be totally unacceptable. A statement that a soil is in a condition of "initial liquefaction with a limiting cyclic strain potential of X percent" seems to provide a more specific and graphic description of the situation than a statement that the soil is "cyclically mobile".

However, in the long run, it matters little which terminology is used so long as the phenomena are understood and used in the same manner throughout the profession. It is hoped that the above explanation will serve to clarify any misunderstandings which may have arisen through the use of different terminology by different investigators and emphasize that there is in fact apparently a high degree of agreement on many aspects of the soil liquefaction phenomenon.

## 2. Method of Soil Formation (Soil Structure)

Recent investigations by Pyke (1973), Ladd (1974) and Mulilis et al (1975) have provided clear evidence that the liquefaction characteristics of saturated sands under cyclic loading are significantly influenced by the method of sample preparation or soil deposition. Typical results showing the magnitude of this effect, as reported by Mulilis et al, are shown in Fig. 3. It is clear that, depending on the method of sample preparation, the stress ratio required to cause initial liquefaction in a given number of stress cycles for sands having the same density may vary by as much as 100%. In this same study measurements were also made of the structures of the samples prepared by the different methods and it was clearly shown that the different liquefaction characteristics were associated with different structural arrangements of the sand grains. Clearly this factor must be considered in performing

laboratory tests to determine in-situ characteristics for design studies.

### 3. Period Under Sustained Load

Several engineers have suggested that the liquefaction characteristics of in-situ deposits are influenced by the age of the deposit (e.g. Ohsaki, 1969; Casagrande, 1975). Confirmation of this effect has been obtained in recent laboratory studies where identical samples have been subjected to sustained loads for periods ranging from 0.01 to 95 days prior to testing; in this relatively brief period from a geological point of view, the samples showed an increased resistance to initial liquefaction in terms of stress ratio of about 25 percent. While laboratory extrapolation of this data to much longer times is virtually impossible, some light on the effects of tens or hundreds of years of sustained pressure may be obtained by comparing the characteristics of good quality undisturbed samples with those of freshly deposited samples of the same sand, tested at the same density and confining pressure as shown in Fig. 4 (Mulilis et al, 1976). This type of data, coupled with reasonable extrapolation of the laboratory test data, indicates the possibility of increases in liquefaction resistance of the order of 75 percent over the stress ratios causing liquefaction of freshly deposited laboratory samples, due to long periods of sustained pressure in older deposits. It seems likely that this strength increase is due to some form of cementation or welding (Lee, 1975) which occurs at contact points between the sand particles, or to the development of a more stable structure due to secondary compression effects.

It may be noted that since the data for field samples shown in Fig. 4 were obtained by comparing the results of tests on undisturbed samples

with those for samples which were freshly prepared by pluviation through air, they reflect the potential effects of differences in structure, effects of sustained loading and effects of sample disturbance. The points shown and the arrows indicate the authors best estimate of sustained loading effects, allowing for other possible differences in sample characteristics

Regardless of the results of the tests on undisturbed samples which might simply be regarded as a guide, the lower bound line in Fig. 4 would seem to be a reasonable lower bound extrapolation of the laboratory data and the magnitude of the effects which can be expected in some soils.

#### 4. Previous Strain History

The importance of factors other than density on the liquefaction characteristics of sand under cyclic loading conditions was first demonstrated by Finn, Bransby and Pickering (1970) who showed, by means of simple shear tests on small-scale samples of saturated sand, that the liquefaction characteristics were influenced by the strain history to which they had previously been subjected. Similar results have subsequently been presented by Bjerrum (1973), Lee and Focht (1975) and Seed, Mori and Chan (1975). A typical example, showing the liquefaction characteristics of a freshly deposited sand and a similar deposit which had previously been subjected to a strain history representative of several very small earthquake shocks is shown in Fig. 5. Although the prior strain history caused no significant densification of the sand, it increased the stress ratio required to cause initial liquefaction by a factor of about 1.5. Much larger increases have been shown for more

severe pre-strain conditions involving more stress cycles and pore pressure increases (Bjerrum, 1973; Lee and Focht, 1975).

##### 5. Lateral Earth Pressure Coefficient and Overconsolidation

Both theory and experimental data show that the stress ratios required to cause initial liquefaction are significantly influenced by the coefficient of earth pressure at rest,  $K_o$ , in a soil deposit. Experimental evidence of the large effects of  $K_o$  on the stress ratios required to cause initial liquefaction and large strains is presented in Fig. 6 (after Seed and Peacock, 1971). These data were obtained by testing samples of saturated sands in a simple shear device after inducing different degrees of overconsolidation, with overconsolidation ratios varying from 1 to 8, to produce different values of  $K_o$ . Previous work by Hendron (1963) shows that values of overconsolidation ratio of the order of 6 to 8 would be likely to produce values of  $K_o$  of 1 or more. It may be seen that for this sand with values of overconsolidation ratio greater than 5, the stress ratios required to cause liquefaction were increased by at least 50 percent.

Similar effects of  $K_o$  are indicated by test data presented by Ishibashi and Sherif (1974) and by analytical studies by Finn et al (1970), Seed and Peacock (1971) and Castro (1975).

##### Liquefaction Characteristics of In-Situ Deposits

In the previous section the effects of five factors have been described, each of which may increase the stress ratio required to cause initial liquefaction of a freshly deposited sand deposit by a factor ranging from 1.5 to 2 or more. Recognizing that one or more of these factors will influence the liquefaction characteristics of all

in-situ deposits, and that the test data shown in Figs. 1 and 2 were obtained on freshly deposited, normally consolidated samples having no prior strain history and the weakest type of structure as indicated by Fig. 3, it would seem reasonable to believe that the stress ratios required to cause initial liquefaction of in-situ deposits in any given number of stress cycles will be significantly greater than those indicated in Fig. 1. In fact, if the data in Fig. 1 are considered a probable approximate lower bound for confining pressures of the order of 1 kg/sq cm, a likely range of values of stress ratios required to cause initial liquefaction in 10 stress cycles is illustrated in Fig. 7 (Seed, 1976). The appropriate value for any given sand within the range indicated will depend on its relative density, grain characteristics, method of placement or soil structure, strain history, age since deposition or placement, and  $K_o$  (or overconsolidation ratio) and all of these factors need to be considered in selecting design values. Clearly this can only be done by testing high quality undisturbed samples maintaining the effects of the factors listed above to the fullest possible extent, although even this procedure is likely to lead to some loss of strength and will not necessarily lead to a reproduction of the in-situ values of  $K_o$ .

Commensurate with the greater liquefaction resistance resulting from in-situ conditions, it might also be expected that the limiting strain potentials of in-situ sands would possibly be less than those indicated in Fig. 2 for the freshly-deposited samples tested by DeAlba et al (1975). Thus a corresponding range of limiting strains for samples at different relative densities is indicated by the shaded zone in the upper part of Fig. 7. On this basis, deposits with relative densities

greater than 80 percent would have very low strain potential under cyclic loading conditions, even if they developed a condition of initial liquefaction. On the other hand there is evidence to suggest that the magnitude of limiting strains depends primarily on the relative density regardless of other factors such as aging and soil structure, and that they will vary considerably depending on the confining pressure acting on the sand.

For purposes of comparison, the author's interpretation of the views of Casagrande on this question are also indicated approximately in Fig. 7. Casagrande (1976) states: "Medium-loose sands in the range between 40 and 60 percent (relative density) may be slightly contractive or slightly dilative; and in-situ they may respond to cyclic loading with strains of objectionable magnitude but rarely with actual liquefaction. In strongly dilative, anisotropically-consolidated sands in-situ, with relative densities greater than about 70%, I consider it normally impossible for cyclic pore pressures to approach or equal the confining pressure because dilatancy will automatically cause the grain-structure to off-set loss of strength by 'bracing itself,' so to speak, requiring only minute strains." The curve labelled Casagrande in Fig. 7 is simply intended to reflect this point of view.

On the other hand, Bjerrum (1973) concluded from tests on sand at a relative density of 80 to 85 percent, that for the design of gravity structures on the ocean floor, "although a higher undrained shear strength may be mobilized in a dilating sand....its mobilization requires a straining beyond what is believed to be acceptable for a structure of this type." Clearly the matter of acceptable strains must be considered in assessing the significance of values of limiting strain potential, and a strain

level which may be unacceptable for an ocean-bottom structure may be of little or no consequence in a deformable structure such as an earth dam.

#### Liquefaction Characteristics of Undrained Samples

Having thus considered the probable liquefaction characteristics of in-situ deposits, it is of interest to consider the degree to which these characteristics may be determined by tests on undisturbed samples. Clearly the validity of any liquefaction analysis procedure based on a comparison of earthquake-induced stresses with those determined to cause liquefaction or undesirable strains of undisturbed samples will depend on the extent to which the in-situ characteristics are maintained in the sampling and handling process.

#### Volume Changes in "Undisturbed Samples"

Some light on the volume changes occurring during undisturbed sampling is provided by studies conducted by the Corps of Engineers Waterways Experiment Station (1952) who found that for loose to medium dense sands, sampling is likely to lead to some degree of densification, while for dense sands with relative densities greater than about 75 percent, sampling was likely to be accompanied by some degree of dilation. It should be noted that either a loosening or a densification of sand in this way involves relative movements between sand grains and therefore a probable loss of any cementation effects. This would tend to offset any increased resistance to liquefaction due to densification of looser sands, but for denser sands with relative densities greater than about 75%, both dilation and an accompanying loss of cementation are likely to result in a marked reduction in resistance to liquefaction. However it

is not immediately clear how sampling disturbance might influence the effects of prior seismic history. A detailed study was therefore undertaken to determine the effects of sample disturbance on the liquefaction characteristics of sand whose resistance to liquefaction had been increased by prior seismic straining.

Effect of Sample Disturbance on Liquefaction Characteristics  
of Sands with Prior Seismic History

The large-scale testing equipment which permitted the testing of sand beds 90" long by 42" wide and 4" deep under simple shear conditions (DeAlba, et al, 1976) provided a convenient means for comparing the liquefaction characteristics of undisturbed samples extracted by different sampling procedures from sand beds prepared with and without prior seismic histories, the latter being sufficiently low that they would not induce large pore pressure increases in the sand deposit.

Thus for example, by means of the large scale equipment, stresses representative of any given earthquake could be induced on a thin layer of sand loaded to represent an elemental layer at various depths in a soil deposit. Sand beds were prepared by pluvial deposition, which seems to produce for this sand a structure and characteristics similar to those of a freshly sedimented deposit (see Fig. 3). After being saturated the sand bed was subjected to cyclic stress applications to determine the relationship between cyclic stress level and the number of cycles required to cause initial liquefaction. For the purposes of the present investigation, tests were performed on Monterey No. 0 sand, a uniform medium sand, deposited to a relative density of 54% and subjected to a confining pressure representative of that existing at a depth of 15 ft in the ground with a water table 4 ft below the ground surface (about

1200 psf). The results of such tests are shown in Fig. 5.

In addition sand beds were prepared and tested after the sand had been subjected to a prior seismic history. For this purpose the sand samples were deposited and saturated as described above. However after being saturated, the sand layer was subjected to a series of small shocks designed to represent the effects of a series of small (magnitude  $\approx 5$ ) shocks occurring over a period of years. After each small earthquake, which built up a small residual pore pressure in the sand, the pore pressure was allowed to dissipate and the layer to reconsolidate under the initial overburden pressure. Finally after 5 such small events, the sand was subjected to a larger shock to determine the stress conditions required to cause it to develop a condition of initial liquefaction (pore pressure equal to confining pressure). In the present test program the sand was subjected to five shocks representative of magnitude 5 earthquakes occurring at a distance of about 5 miles. The maximum ground surface acceleration in these earthquakes was considered to be about 0.18g and the duration to be consistent with the development of 2-1/2 to 3 cycles of motion at a stress level of 220 psf. Thus the cyclic stress ratio, that is the ratio of the cyclic shear stress to the effective vertical stress, for each of these shocks was 0.185.

A comparison of the liquefaction characteristics of the sand beds tested with and without a prior seismic history of the type described is shown in Fig. 5. It is readily apparent that the effect of the prior seismic history was to cause a significant increase in the cyclic stress ratio required to cause initial liquefaction of the sand.

Once this result was established, similar beds of sand were prepared, with and without the same seismic histories, and samples of sand

were extracted by various procedures for testing in cyclic triaxial tests. In all cases, samples were extracted using thin wall sampling tubes with a sharpened cutting edge. However in some cases the cutting edge was under-reamed to provide a slightly smaller diameter at the entrance to the tube than inside the tube. The characteristics of the sampling tubes were defined by the area ratio  $C_a$  and the inside clearance ratio  $C_i$ , where

$$C_a = \frac{D_o^2 - D_i^2}{D_i^2} \times 100$$

and  $C_i = \frac{D_m - D_i}{D_i} \times 100$

where  $D_o$  = outside diameter of sampling tube

$D_m$  = inside diameter of sampling tube

and  $D_i$  = inside diameter of cutting edge at entrance to tube as shown in Fig. 8.

In the first series of tests, samples were extracted from both types of beds using the utmost care and sampling tubes for which  $C_a = 10.6\%$  and  $C_i = 0.8\%$ . The sampling tubes were pushed carefully into the beds of moist sand, creating a minimum of disturbance, the sand surrounding the tubes was then trimmed away, a thin metal plate was pushed under the bottom of the tube and the sample extracted. The moist sand was then extruded directly into a pre-extended membrane, provided with a cap and base, saturated, subjected to a confining pressure equal to the overburden pressure used in the tests on the in-situ beds, and subjected to a cyclic triaxial test to determine its liquefaction characteristics. This method of sample preparation and testing is believed

to be representative of procedures generally used in past and current engineering practice.

The results of such a series of tests on samples extracted from sand beds with and without seismic histories using a sampling tube with under-reamed edges and on samples prepared by pluviation directly into a mold in the triaxial cell are shown in Fig. 8. It may be seen that all samples had essentially the same resistance to liquefaction and, for practical purposes, the effects of the prior seismic history on the in-situ sand bed were apparently lost in the sampling and testing process.

The effects of driving the sampling tube into the sand bed with a prior strain history are illustrated in Fig. 9, where the stress ratios required to cause initial liquefaction for samples extracted after striking the sampling tube with 20 and 50 blows respectively are compared with those of samples extracted by carefully pushing the sampling tube into the sand. Again the effect of this simulated driving of the sampling tube had apparently little effect on the liquefaction resistance of the samples and any influence of prior strain history was lost in the sampling, handling and testing process. However it was noted that following extrusion of the samples from the tubes, there was a very slight slumping of the test specimen, evidenced by the fact that the diameter at the bottom was typically several thousands of an inch greater than that at the top. This slumping alone could be responsible for a significant change in cyclic loading characteristics which might even exceed or mask any effects due to sampling disturbance. Such effects are particularly likely to occur in clean, medium and coarse sands such as that used in this investigation where capillary effects are small.

The comparative effects of using sampling tubes with and without under-reamed edges are shown in Figs. 10 and 11. Fig. 10 shows comparative data for samples extracted from sand beds with no seismic strain history and Fig. 11 shows similar data for samples from sand beds with a prior strain history. Again the effects of the prior strain history are apparently lost in the sampling and handling process although to a slightly less degree in the samples extracted with straight-sided tubes. This effect may well be due to a slightly higher density for samples extracted in this way.

Finally to investigate whether the effects of prior strain history could be maintained in samples obtained by any type of extraction procedure, three series of tests were conducted on samples which were deposited directly in a mold on the triaxial cell and tested as follows:

Series 1. Samples were deposited by pluviation, saturated and then subjected to cyclic triaxial tests until a condition of initial liquefaction was reached.

Series 2. Samples were deposited by pluviation, saturated and then subjected to several series of cyclic stress applications, each inducing a small pore pressure increase followed by drainage, in order to induce a strain history effect. The samples were then subjected to increased cyclic stress ratios to determine the conditions required to cause initial liquefaction.

Series 3. Samples were prepared and given a prior strain history effect as in Series 2. However before testing for liquefaction characteristics, the confining pressure on

the samples was reduced to 0.5 psi to simulate the effect of "perfect sampling"; that is, removal of the confining pressure without any disturbance of the samples. The initial confining pressure was then restored and the stress ratios required to cause initial liquefaction were determined as for Series 1 and 2.

The results obtained from these three series of tests are compared in Fig. 12, from which it may be seen that although a prior strain history increased the liquefaction resistance of the samples as before, about 35 percent of this effect was lost simply as a result of the pressure reduction prior to testing. Under these conditions it is perhaps not surprising that virtually all of the effects of prior strain history were lost when the samples of this sand were slightly disturbed during sampling as well as having the confining pressure reduced by sample extraction and probably further disturbed by sample handling in the testing procedure.

#### Liquefaction Characteristics of Undisturbed Samples

In the light of the above results, it seems likely that the effects of prior strain history in increasing the liquefaction resistance of clean sands, which must inevitably develop to some extent for deposits in seismic environments, will be lost to a significant extent even for the most careful sampling, handling, and testing procedures of the type described above, and test data even for good quality undisturbed samples will therefore often be unduly conservative for this reason alone.

Coupled with the loss of cementation effects produced by long-term loading, possible loosening during sampling and the effects of increased  $K_o$

values, it seems likely that the liquefaction resistance of medium dense and dense undisturbed samples of clean sands in laboratory tests will often be very much lower than those of in-situ deposits.

Further evidence to support this belief is provided by the data in Figs. 13 and 14. Fig. 13 shows the results of tests on undisturbed samples of sand taken from a depth of about 80 feet in a heavily over-consolidated deposit having an overconsolidation ratio of about 8. Samples were first tested, after saturation under a confining pressure similar to that existing in the field, in the condition in which they were received in the laboratory. A second series of tests was then undertaken in which an effort was made to re-establish the in-situ condition by first subjecting the samples to an anisotropic stress condition representing the maximum stresses developed during the geologic history of the deposit and then gradually reducing this pressure condition to an ambient pressure equal to that used in the first test series. The effects of this treatment, which presumably reproduced to the fullest extent possible, the condition of the in-situ soil, was to increase the stress ratio required to cause liquefaction by about 100 percent. Clearly it is important to determine effects of this magnitude by re-creating the in-situ structure of a sand if meaningful test data for use in analyzing the liquefaction potential of a deposit, is to be obtained.

Finally, Fig. 14 compares test data reported by Castro (1975) for 'undisturbed' samples of sand with test data obtained on large scale samples which were freshly deposited by pluviation to different initial relative densities and correspondingly different values of penetration resistance (Mulilis, 1975). Although the laboratory test specimens had

no opportunity to gain resistance from long-term pressure application, prior seismic history or increases in  $K_o$ , the stress ratios required to cause initial liquefaction for samples having a given penetration resistance were very much larger than those of the undisturbed field samples from deposits with high penetration resistance values. It is difficult to rationalize these results except by concluding that the undisturbed field samples must have been seriously loosened during the sampling and handling process, in spite of the care taken to preserve their initial density and overall condition.

On the other hand it is interesting to note that there is no great difference in liquefaction characteristics for samples having moderate penetration resistance values indicative of loose to medium dense sands. This may well be due, among other reasons, to the fact that such samples do not dilate or change significantly in density during sampling and thus do not suffer nearly the same degree of loss of liquefaction resistance as do very dense cohesionless soils.

In view of this it may be that good quality undisturbed samples of some medium dense sand deposits containing sufficient fines to maintain the in-situ structure of the grains will provide a reasonable indication of the true resistance to liquefaction of the in-situ material, possibly because the effects of environmental factors such as geologic and seismic histories are not entirely lost during sampling and handling or because they are compensated to some extent by a slight increase in density during sampling. That this is likely to be the case is evidenced by the data in Fig. 4 where significant effects of long term loading were apparently maintained during the sampling and handling process for some sands. It would seem that retention of in-situ

characteristics is likely to be greater for sands possessing some slight degree of cohesion or significant apparent cohesion due to capillary effects. However for clean medium and coarse sands this is not likely to be the case unless special efforts are made to maintain the structure, say by some procedure such as freezing the soil in some manner to prevent slumping and other structure-destroying effects.

However in the absence of such special procedures such as freezing to maintain density and structure, it seems likely that such effects can never be compensated for in dense sands where the inevitable dilation during sampling and handling will invariably lead to a loss of liquefaction resistance due to (1) a reduction in density, (2) a loss of cementation or long-term loading effects and (3) a possible loss of seismic history effects. The potential magnitude of these effects is likely to be the dominant factor in evaluations of the liquefaction potential of relatively dense sands.

#### Conclusion

In the light of the preceding discussion and because of the potential variations in the effects of sample disturbance on the measured liquefaction characteristics of undisturbed samples, it is apparent that considerable judgment is required to correctly assess the liquefaction characteristics of in-situ deposits from the results of laboratory tests, even if they are conducted on good quality undisturbed samples using conventional procedures.

It would seem that the design engineer confronted with the need to evaluate the possible liquefaction potential of a deposit has three choices:

1. To take the best possible undisturbed samples and then try to reconstruct their true field characteristics by following some procedure such as that illustrated in Fig. 13, or by allowing for sample disturbance effects by reasonable judgment;
2. To devise and utilize a procedure such as freezing the samples during sampling and handling and thaw them prior to testing in order to possibly maintain soil density and structure; however the use of such a procedure still requires investigation as to its usefulness for this purpose;
- or      3. To be guided by the known field performance of sand deposits correlated with some measure of in-situ characteristics, such as the standard penetration test, on the grounds that most factors which tend to improve liquefaction resistance also tend to increase the standard penetration resistance or the results of any other in-situ test which may be adopted as a possible indicator of field liquefaction behavior.

In the best situations it would hopefully be possible to obtain reasonable agreement on the potential for liquefaction using all of these approaches, or at least approaches 1 and 3 (since approach 2 is still under investigation). However without the exercise of considerable judgment or a serious attempt to maintain or recreate the in-situ soil characteristics, the direct use of laboratory test data from tests or even undisturbed samples of moderately dense to dense deposits seems likely to lead to severe over-design in many cases involving clean medium and coarse sands or some degree of over-design in slightly cohesive sands or

sands with a sufficient fines content to create substantial apparent cohesion due to capillary effects.

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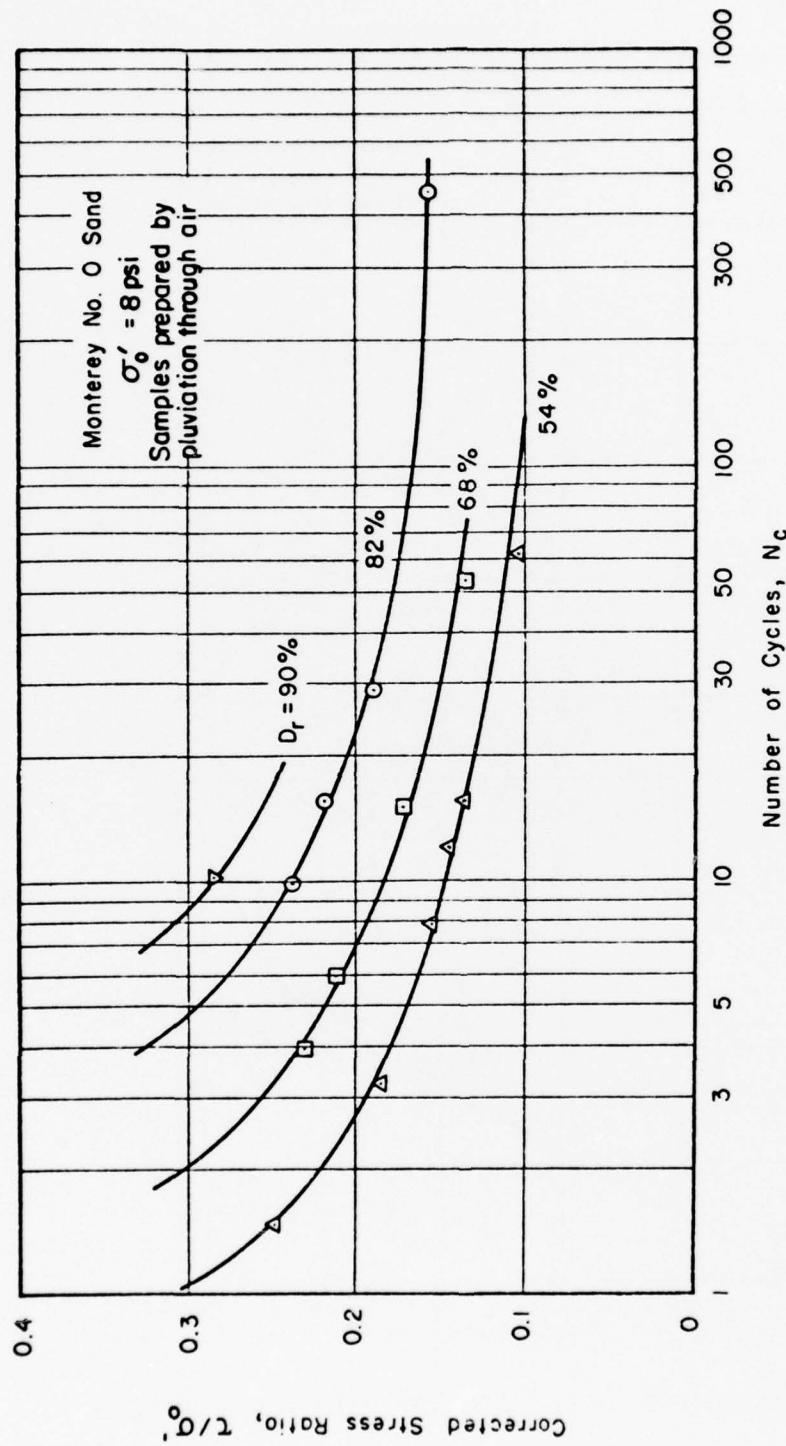


Fig. I CORRECTED  $\tau/\sigma'_0$  VS  $N_c$  FOR INITIAL LIQUEFACTION  
 (after De Alba, Seed and Chan, 1976)

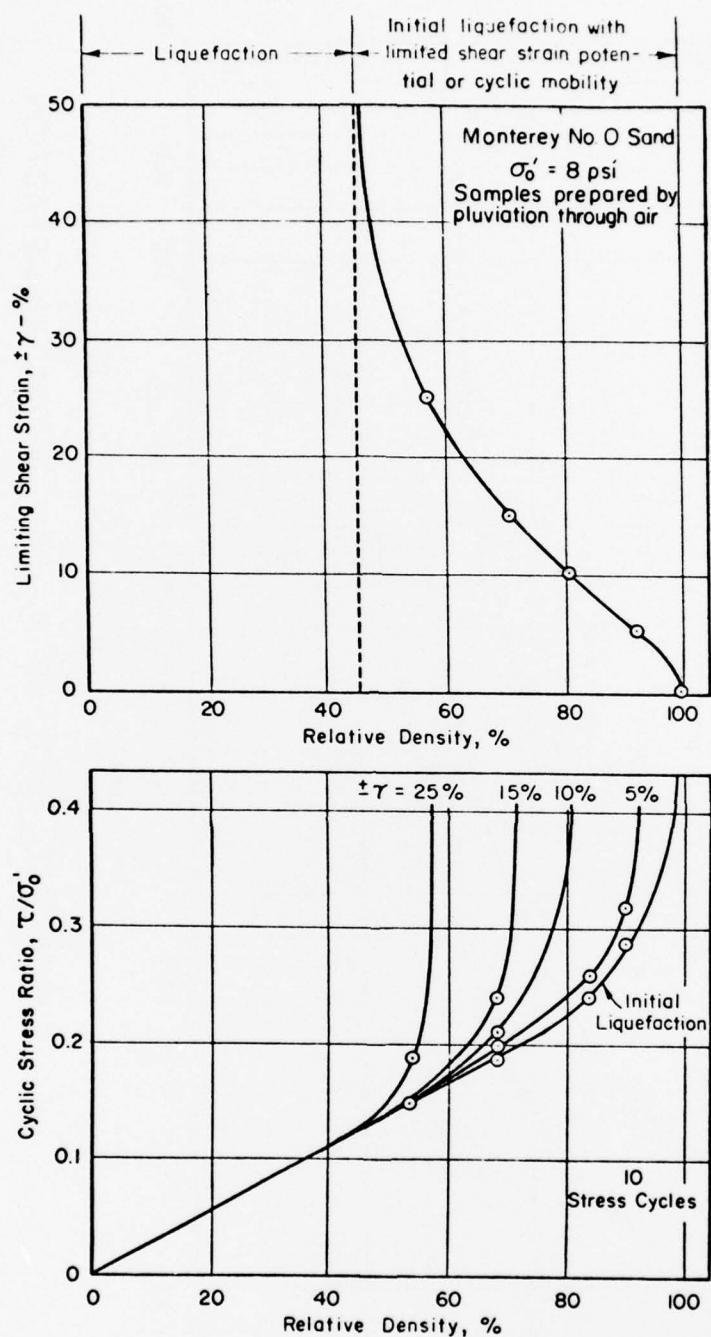


Fig. 2 LIMITING SHEAR STRAINS - 10 STRESS CYCLES

(After De Alba, Chan and Seed, 1975)

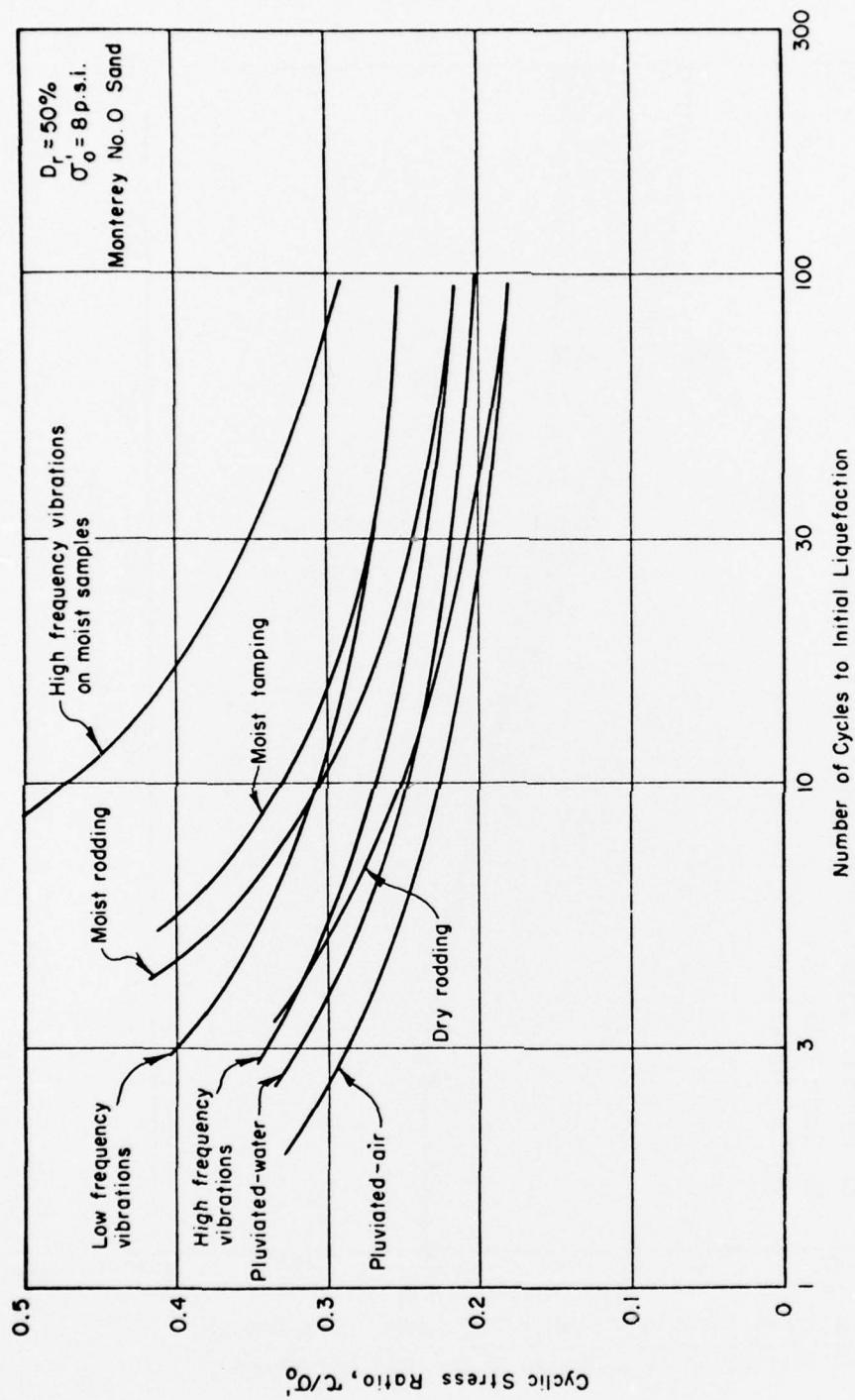


Fig. 3 CYCLIC STRESS RATIO VS NO. OF CYCLES  
FOR DIFFERENT COMPACTION PROCEDURES  
( After Mulinis, Chan and Seed, 1975 )

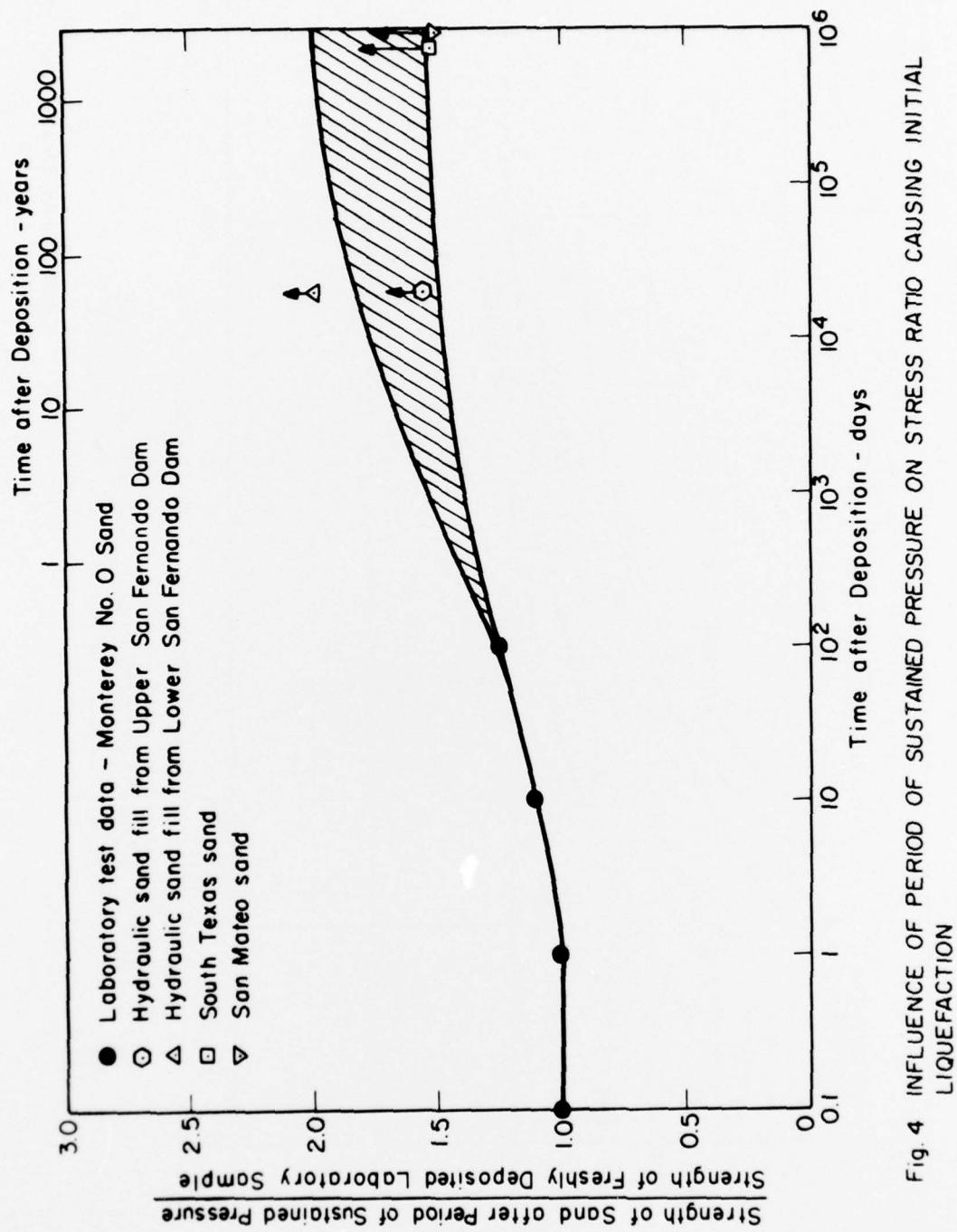


Fig. 4 INFLUENCE OF PERIOD OF SUSTAINED PRESSURE ON STRESS RATIO CAUSING INITIAL LIQUEFACTION

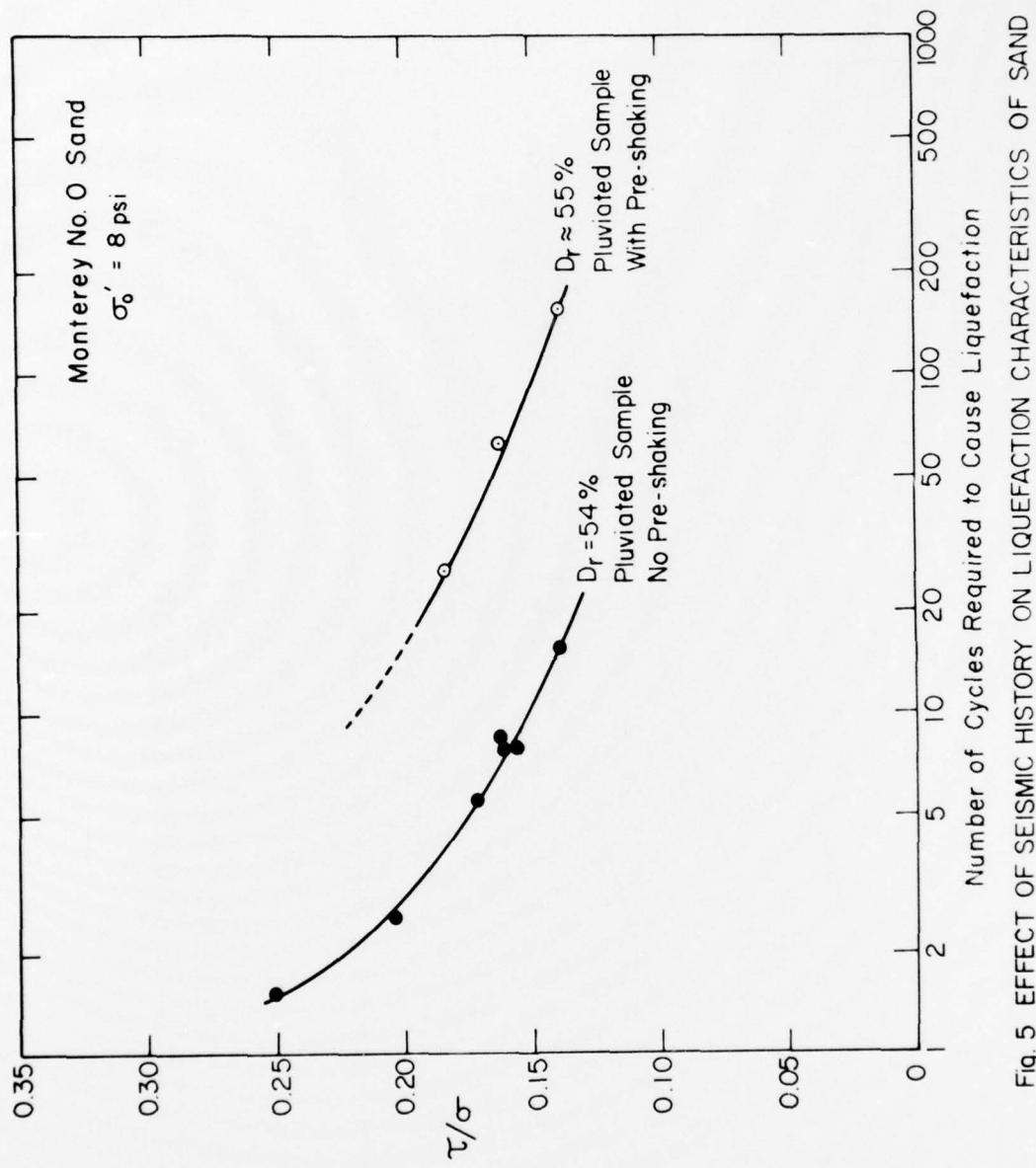


Fig. 5 EFFECT OF SEISMIC HISTORY ON LIQUEFACTION CHARACTERISTICS OF SAND

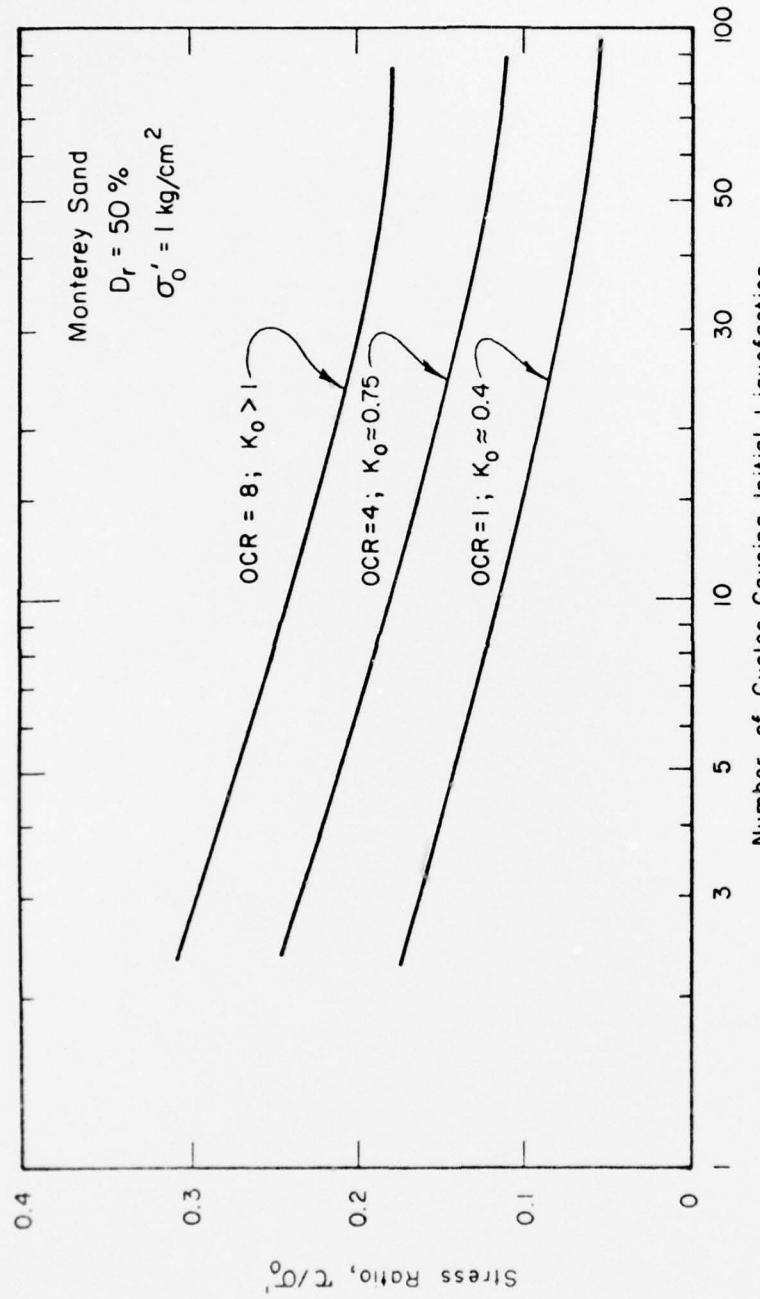


Fig. 6 INFLUENCE OF INITIAL PRINCIPAL STRESS RATIO  
ON STRESSES CAUSING LIQUEFACTION IN SIMPLE SHEAR TESTS

( After Seed and Peacock, 1971 )

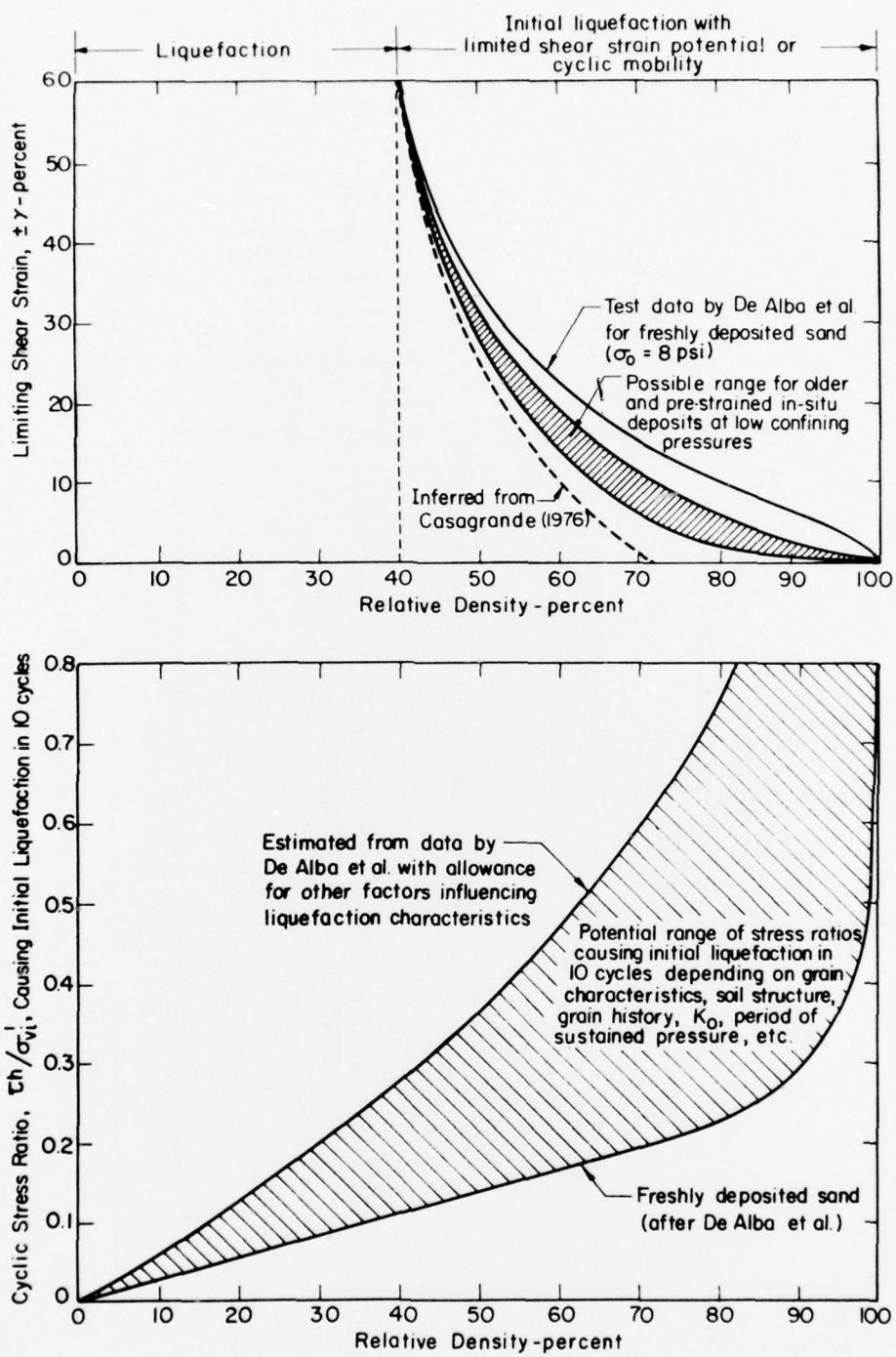


Fig. 7 ESTIMATED RANGE OF LIQUEFACTION CHARACTERISTICS FOR IN-SITU DEPOSITS

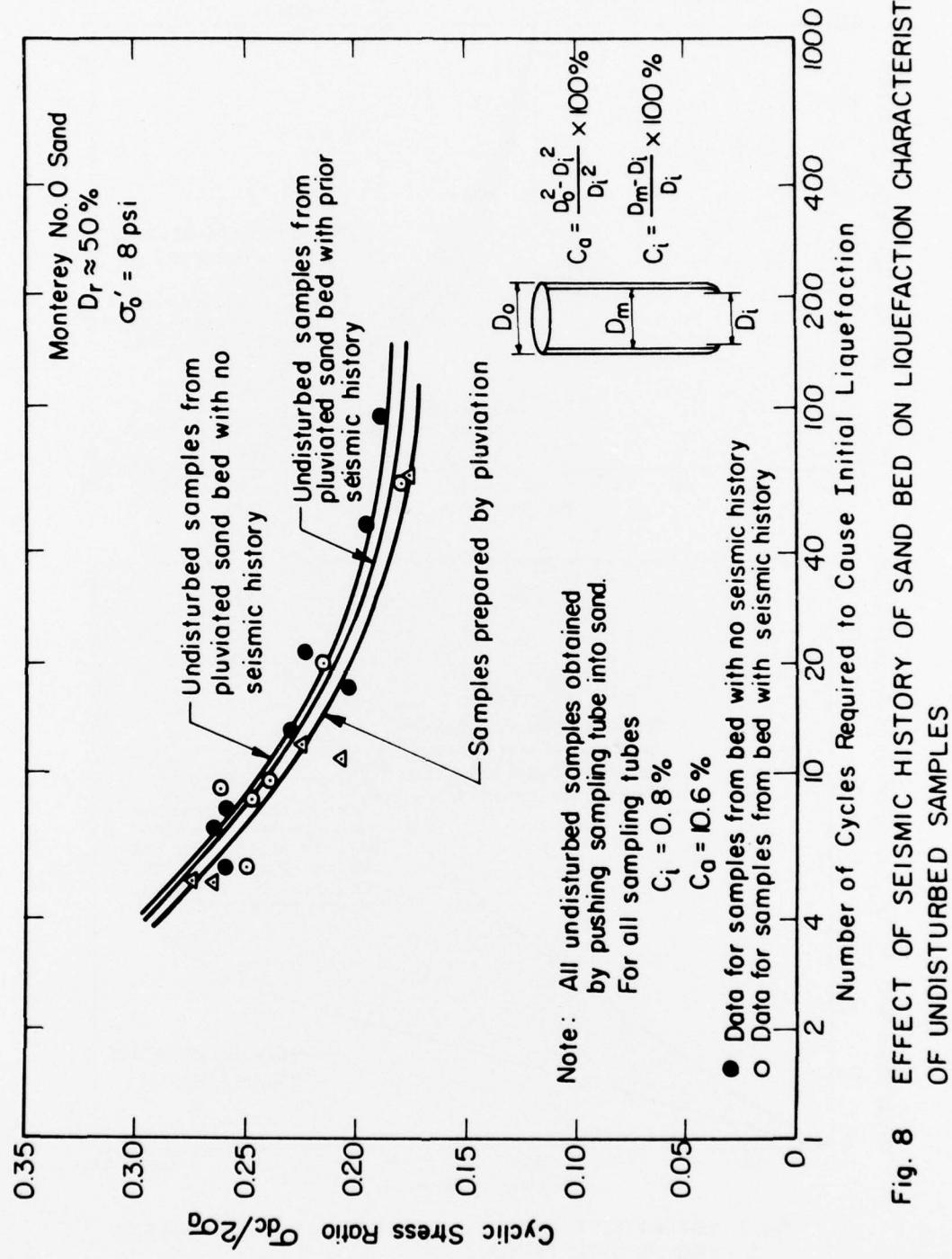


Fig. 8 EFFECT OF SEISMIC HISTORY OF SAND BED ON LIQUEFACTION CHARACTERISTICS OF UNDISTURBED SAMPLES

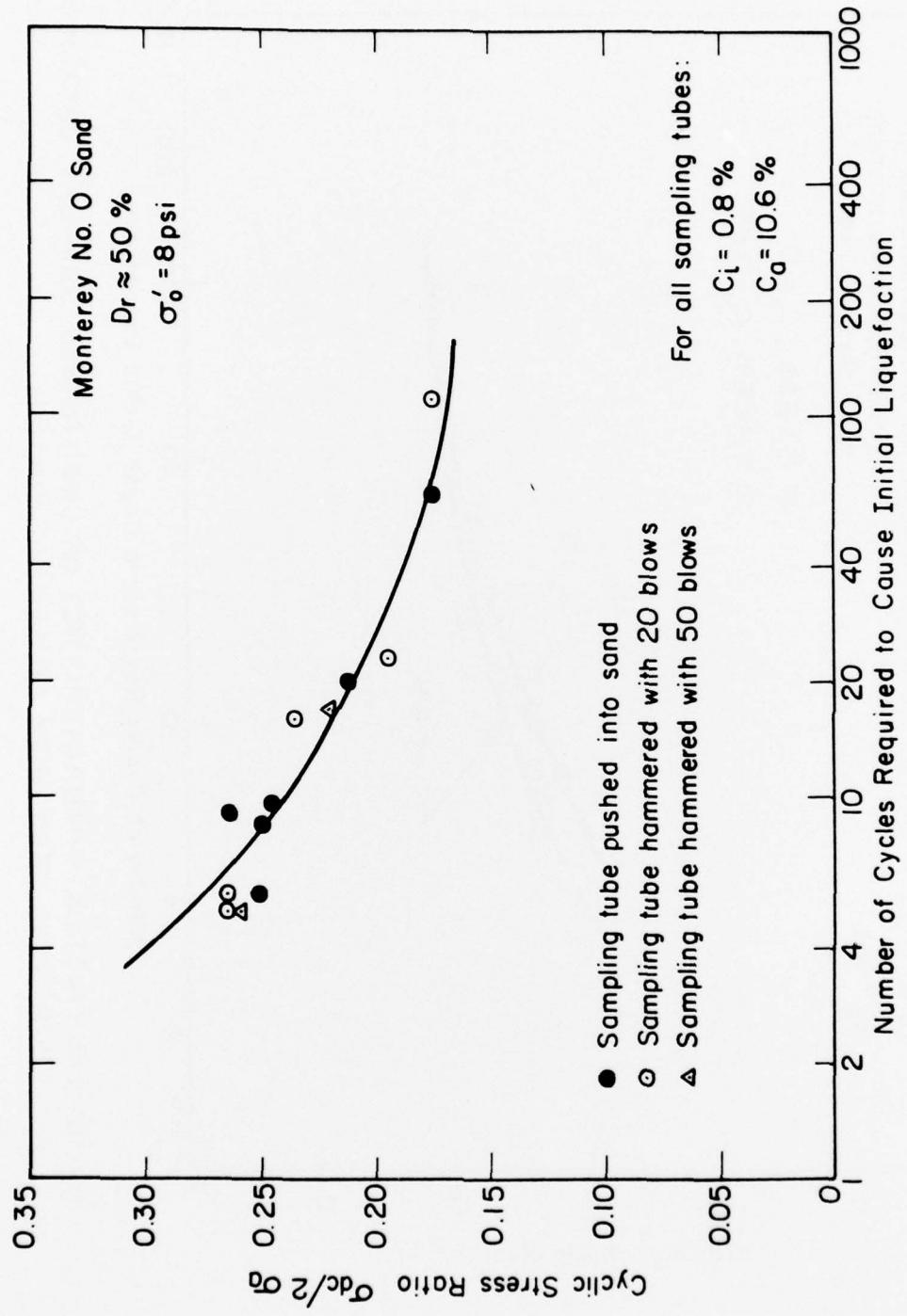


Fig. 9 LIQUEFACTION CHARACTERISTICS OF UNDISTURBED SAMPLES OBTAINED FROM SAND BEDS WITH PRIOR SEISMIC HISTORY

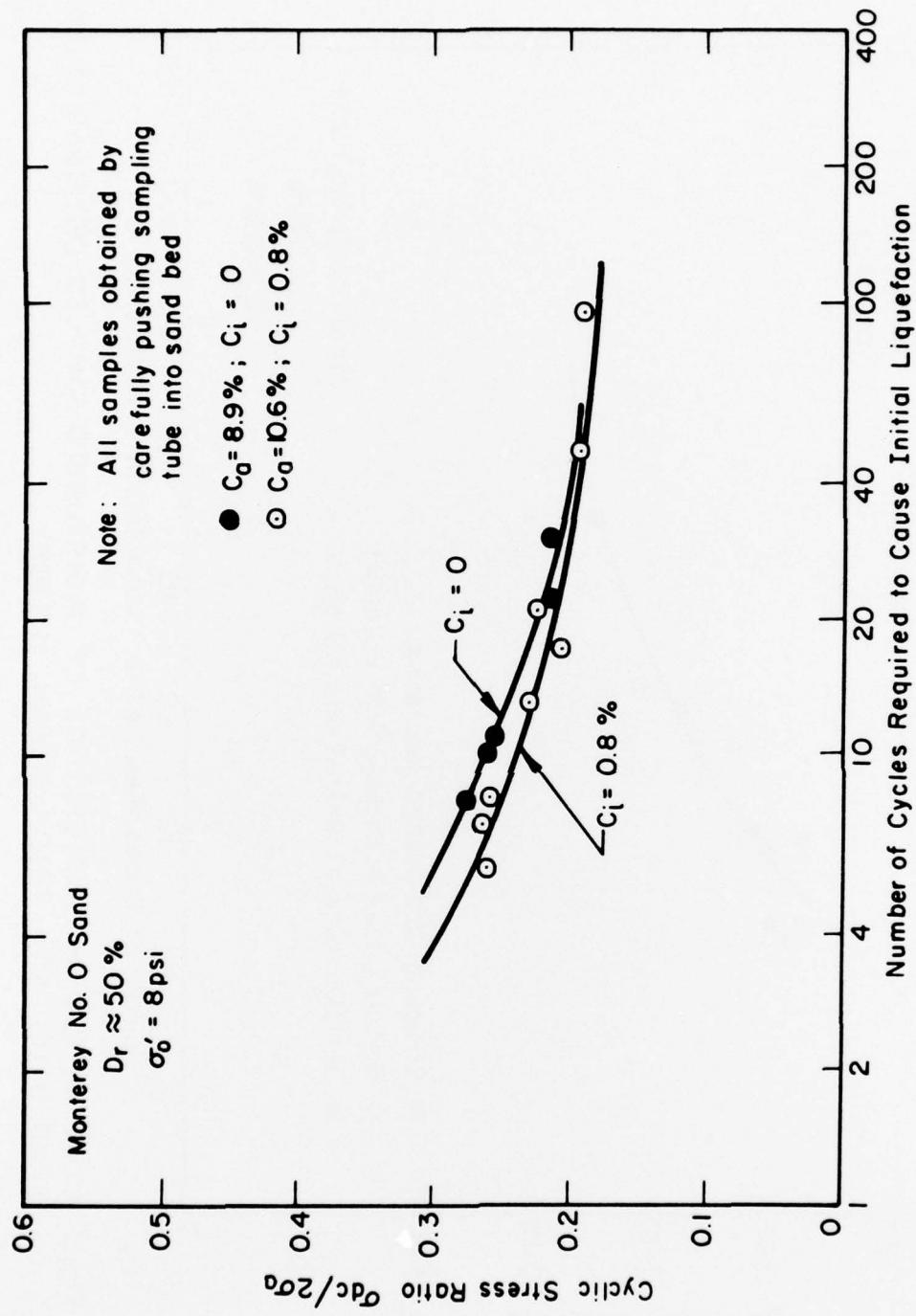


Fig. 10 LIQUEFACTION CHARACTERISTICS OF UNDISTURBED SAMPLES OBTAINED FROM SAND BEDS WITH NO SEISMIC HISTORY

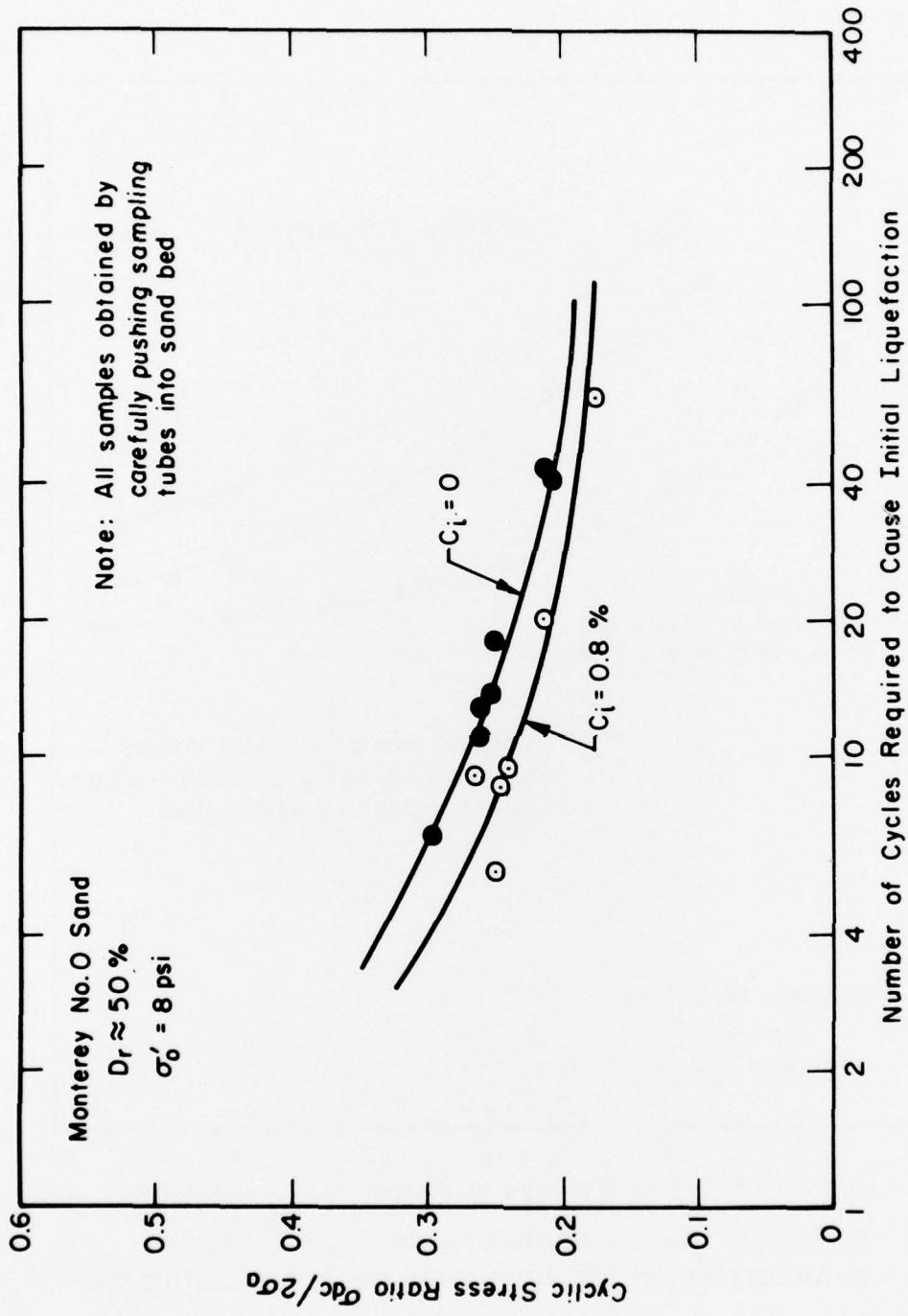


Fig. II LIQUEFACTION CHARACTERISTICS OF UNDISTURBED SAMPLES OBTAINED FROM SAND BEDS WITH PRIOR SEISMIC HISTORY

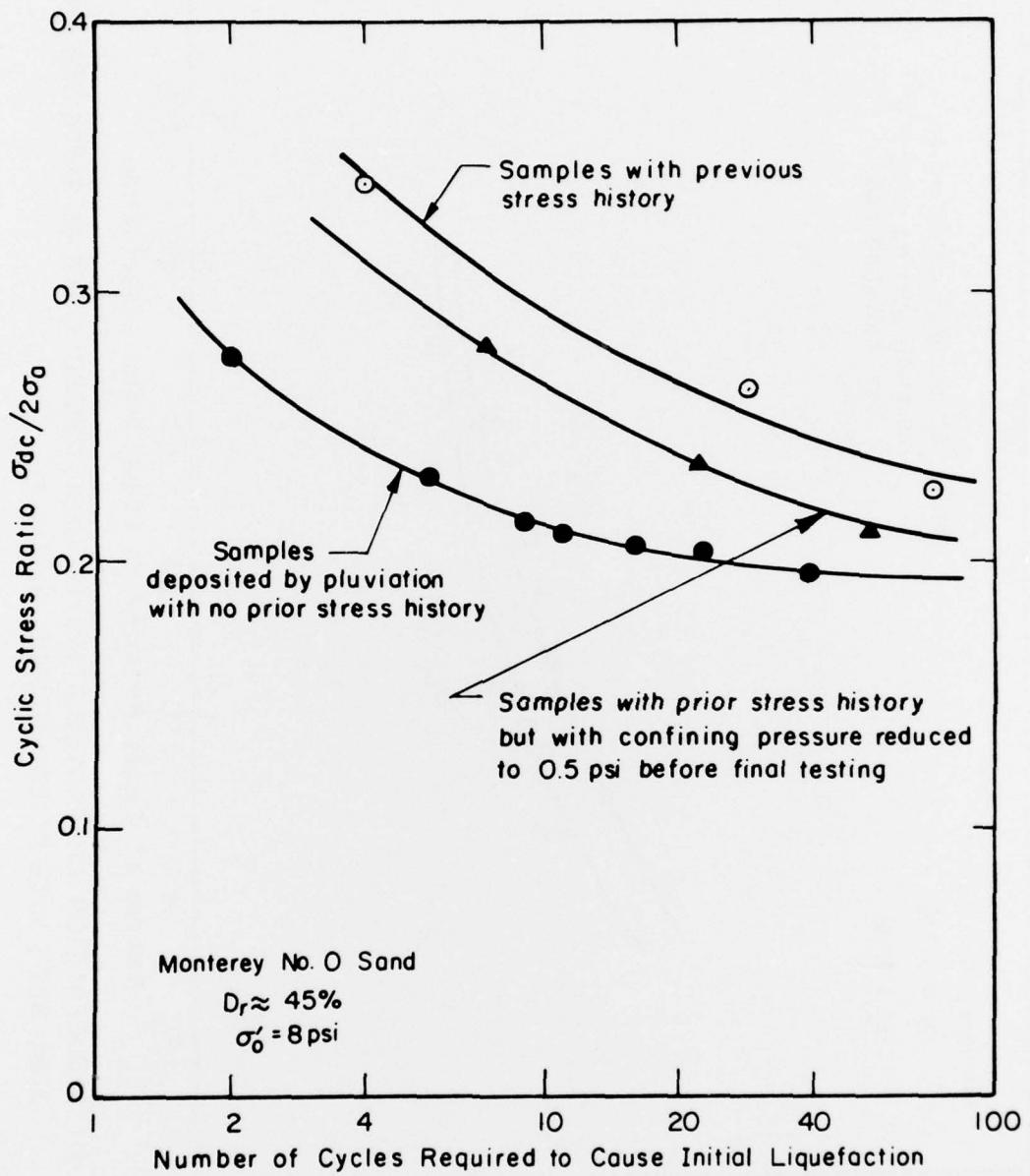


Fig. 12 EFFECT OF STRESS REDUCTION ON LIQUEFACTION CHARACTERISTICS OF SAND WITH PRIOR STRESS HISTORY

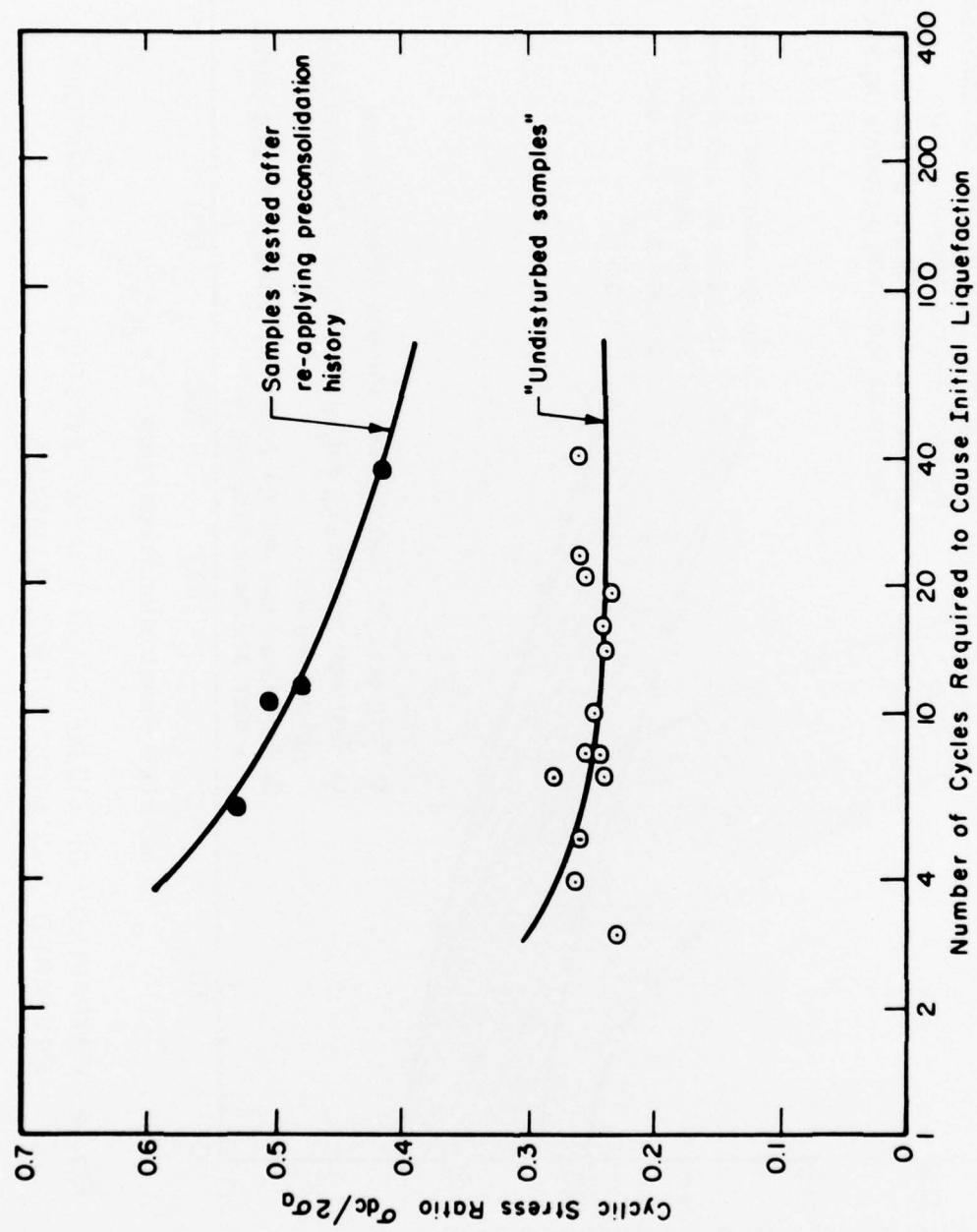


Fig. 13 EFFECT OF RECONSOLIDATION ON CYCLIC LOADING CHARACTERISTICS OF UNDISTURBED SAMPLES

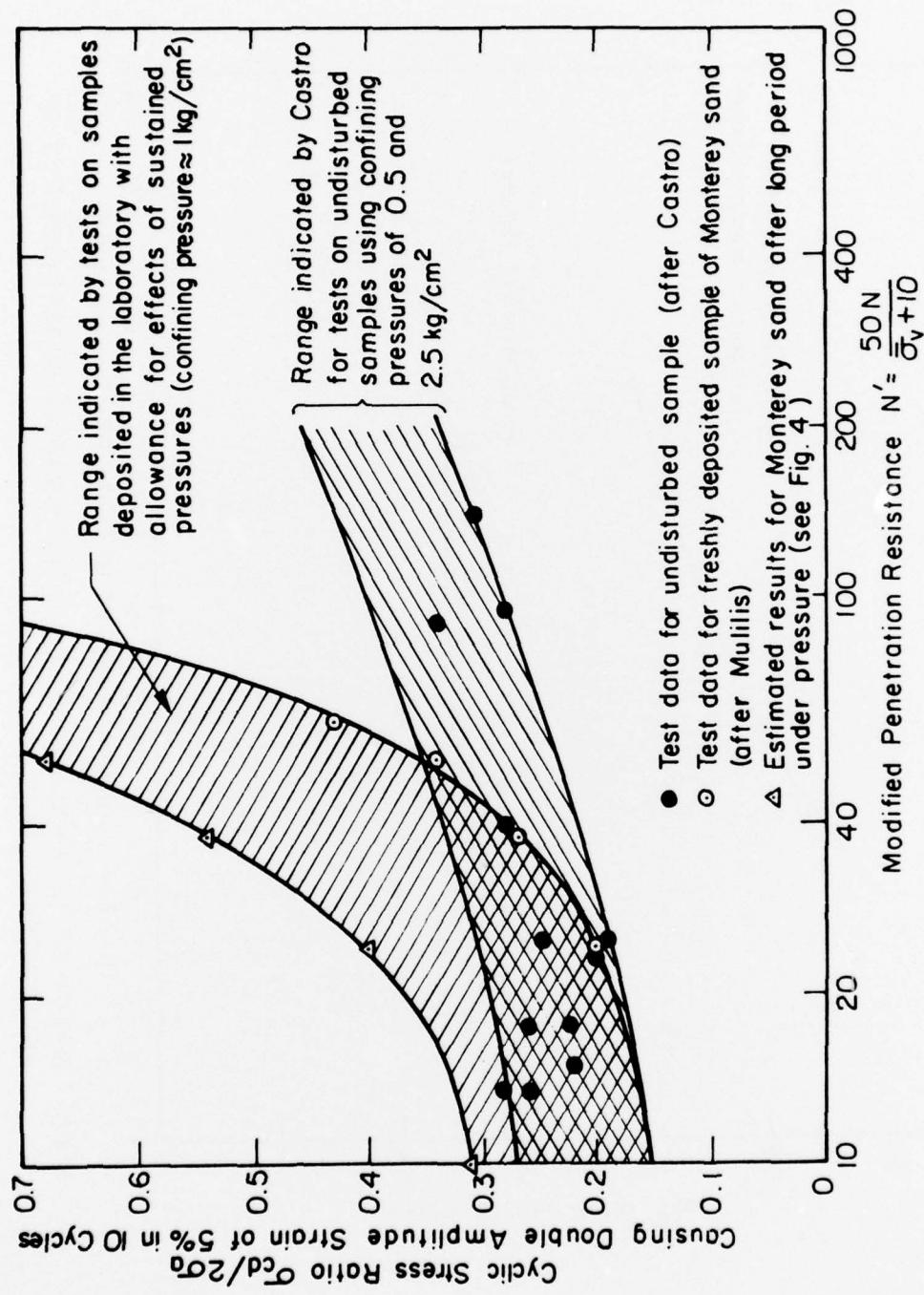


Fig. 14 COMPARISON OF LIQUEFACTION CHARACTERISTICS OF LABORATORY PREPARED AND UNDISTURBED SAMPLES

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